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Post-Injection Monitoring of Stored CO_2 at the Nagaoka Pilot Site: 5 Years Time-Lapse Well Logging Results

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Abstract

Monitoring is the major challenge in CO_2 geological sequestration. At the first Japanese pilot CO_2 injection site (Nagaoka), CO_2 was injected into a thin permeable zone at a depth of 1100 m and the total amount of injected CO_2 was 10,400 tons during the injection period from July 2003 to January 2005. After ceasing of CO_2 injection, well loggings which mainly consist of neutron logging, sonic logging and induction logging have been continued for 5 years. The Nagaoka site may provide the first field data set of post-injection monitoring and essential information on long-term CO_2 behaviour in a saline aquifer. In this paper reports the results of formation pressure, well logging and fluid sampling aiming to improve understanding of CO_2 long term behaviour in the reservoir. The results of time-laps well logging provide the evidences of the solubility trap and residual trap in progress at Nagaoka, suggesting CO_2 is stored safely in a complex sandstone reservoir.

Keywords: CO_2; post-injection; monitoring; trapping mechanism; aquifer; geological storage

1. Introduction

Carbon dioxide capture and storage (CCS) is believed to the most practical technology available to mitigate greenhouse gas emissions from large-scale fossil fuel usage. At the Hokkaido Toyako Summit in 2008, G8 leaders committed to undertake the actions for commercialising CCS technologies. It is considered that storage security will increase with CO_2 trapping processes; (1) structural trapping, (2) residual gas trapping, (3) solubility trapping and (4) mineral trapping. To ensure safety of CO_2 storage for a long time, monitoring, verification and accounting (MVA) is required. One of the key issues of evaluating CO_2 storage security is to provide evidences of existence of immobile CO_2 (residual CO_2, dissolved CO_2 and mineralized CO_2) in the reservoir.

Monitoring is the major challenge in CO_2 geological sequestration. At the first Japanese pilot CO_2 injection site (Nagaoka), CO_2 was injected into a thin permeable zone at a depth of 1100 m and the total amount of injected CO_2 was 10,400 tons during the injection period from July 2003 to January 2005. Not only CO_2 injection period but also after ceasing of the injection, well loggings which mainly consist of neutron logging, sonic logging and induction logging have been continued for 5 years. The Nagaoka site may provide the first field data set of post injection

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monitoring and essential information on long-term CO_2 behaviour in a saline aquifer. In this paper reports the monitoring results of formation pressure, well logging and fluid sampling aiming to improve understanding of CO_2 behaviour in a sandstone reservoir.

2. Nagaoka Site

The first Japanese project of CO_2 geological storage has been conducted at the Minami-Nagaoka gas field so called the Nagaoka site. The injection and monitoring project was conducted between FY2000 and FY2007. The post-injection monitoring project started from FY2010, this April. We decided to collect new field data in this summer.

Target reservoir is a saline aquifer of the Pleistocene Haizume Formation with 60m-thick. One injection well (IW-1) and three observation wells (OB-2, -3, -4) were drilled at the east wing of an anticline, dipping at 15° to east-southeast with strike N100°. The OB-2 is located at 40m from IW-1 in the down-dip direction while the OB-3 and OB-4 are located at 120m and 60m in the up-dip direction (Figure 1). Since Zone2 is most permeable layer (ca. 7mD), an injection layer having about 12-m-thick. Top of the Zone2 depth below the surface is 1092, 1108, 1073 and 1084m at IW-1, OB-2, OB-3 and OB-4, respectively.

In this CO_2 injection experiment, 99.9% pure CO_2 from by-product of ammonia production was delivered by 8-ton lorry to the 95-ton CO_2 vessel in liquefied condition. Prior to inject CO_2, CO_2 was heated. The conditions of temperature and pressure were 32-36 deg-C and 6.6-7.4 MPa at the well head and 45-49 deg-C and 11.9-12.6 MPa at the bottom hole, respectively. Thus the injected CO_2 is in a supercritical phase generally.

The CO_2 injection was conducted at a depth of about 1100 m from July 2003 to January 2005 with total amount of 10,400 tons (Figure 2). The injection rate was 20 ton/day in the first nine months and then it was changed to 40 ton/day after confirming the injectivity of CO_2. At the IW-1 and OB-4, bottom-hole pressures have been monitored and recovered to almost initial conditions (Figure 2).

At the Nagaoka, the reservoir interval in each observation well was cased by fibreglass-reinforced plastic (FRP) instead of steel to enable induction logging. The behaviour of injected CO_2 have monitored by temperature, pressure, well loggings, crosswell seismic tomography and fluid sampling. In this paper we focused on results from the time-laps well loggings, especially neutron logging, sonic logging and induction logging. Details of other monitoring results were described elsewhere [1, 2, 3, 4].

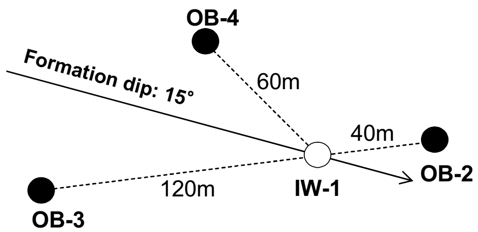

Figure 1 Configuration of the injection well (IW-1) and observation wells (OB-2, -3, -4) at the reservoir depth.

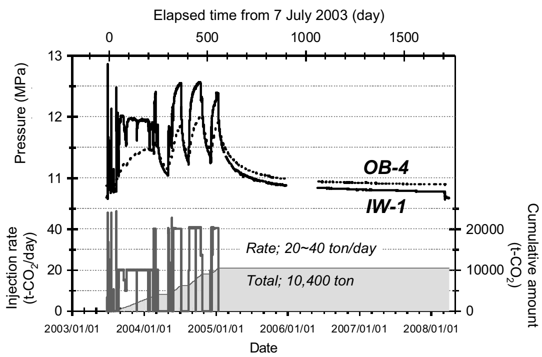

Figure 2 Changes of injection rate, cumulative amount of CO_2, bottom-hole pressure at IW-1 and formation pressure at OB-4.

3. Pressure monitoring

At the IW-1, pressure gauge conveyed tubing was set at the depth of 1072m where about 20 to 30 m above the injection interval. While at the OB-4 pressure gauge was set to out side of a casing at the depth of 1091m, so that this gauge measure the reservoir pressure.

Prior to CO_2 injection, bottom-hole pressure at the IW-1 was 10.7MPa and formation pressure at the OB-4 was 10.8MPa. Pressure responses were synchronized with the CO_2 injection operation at the both wells during injection period (Figure 2). The pressure at the injection well was higher than that at the OB-4 during injection. Just before ceasing of injection, pressures were 12.4MPa at the IW-1 and 11.9MPa at the OB-4. After 5days from the cessation, the pressure at the IW-1 was 11.8MPa and equal to that at OB-4. The pressure drastically dropped about 1MPa during the first one year and then those became gradually stable (10.8MPa at the IW-1 and 10.9MPa at the OB-4). The pressure behaviour shows a slight monotonic decrease in the last 2 years. The decreasing rate is less than 0.04MPa per year. In the post-injection phase, pressure recover processes seem to be two stages.

4. Well Loggings

At Nagaoka, several well logging tools were applied to evaluate how can they response CO_2 behaviour. Neutron logging yields porosity because it responds primarily to the amount of hydrogen which is fundamentally associated to the amount of water present in the pore space. When CO_2 replace formation water, neutron porosity decrease. The reservoir is fully saturated with formation water at Nagaoka. The ratio of change between baseline data and each log data must be equal to CO_2 saturation. Sonic logging acquiers P- and S- wave velocity. P-wave velocity is sensitive to difference between propagation speed in water and that in CO_2. A drastic reduction of P-wave velocity results from very little CO_2 presence. Dual induction logging measures resistivity of a target formation. A resistivity increases as a result of displacement of conductive water by less conductive CO_2.

At the OB-3 where is located 120 m up-dip of the IW-1, any sign of CO_2 arrrival couldn't detect until 37th logs. Vertical distribution of neutron potosity, P-wave velocity and resistivity in the Zone2 at the OB-2 where is located 40 m dwon-dip from the IW-1 and OB-4 where is located 60 m up-dip from IW-1 were shown in Figure 3 and 4. Temporal changes of CO_2 saturation, P-wave velocity and resistivity at the depth of 1116.0 m at the OB-2 (Figure 5 (a)) and 1090.1 m at the OB-4 (Figure 5 (b)) are clearly shown the CO_2 arrival at the observation wells. At the OB-2, arrival of CO_2 was detected by a moderate increase in resistivity, a drastic decrease in P-wave velocity and a decrease in neutron porosity at 14th run when a cummulative amount of about 4000 tons of CO_2 had been injected. At the OB-4, arrival of CO_2 was slso detected by decrease of P-wave velocity and neutron porosity at 17th run when a cummulative amount of about 5500 tons of CO_2 had been injected. Unfortunatlly at the OB-4, the induction log couldn't obtained from surface to Zone2. The FRP casing was applied to the observation well. The lead cable for temperature and pressure sennssor convayed behind casing made much noize on resistivity mesurement.

After the breakthrough of CO_2, CO_2 saturation had increased for a while. The resistivity had increased with increment of CO_2 saturation while the P-wave velocity had less responded. Changes in P-wave velocity and resistivity with CO_2 saturation shows that relationship between CO_2 saturation and P-wave velocity seems to be good up to 20% of CO_2 saturation and over 20% relationship between CO_2 saturation and resistivity become good (Figure 6). These phenomena were supported at the laboratory experimental results [5, 6].

The thickness of Zone 2 is different between at the OB-2 (12 m) and the OB-4 (9 m). But free CO_2 seems to be distributed same layers; two permeable layer interbedded with one less permeable layer (Figure 3 and 4). Contour map of the resistivity change with time at the OB-2 clearly indicates CO_2 bearing layers around 1114 m and 1116 m depths with totally 6 m thick as result from positive changes (Figure 7). Around 1116 m depth, positive change area has decreased with time during post-injection phase as same as decrease of CO_2 saturation (Figure 5 (a)). Negative changes of the resistivity are appeared above and below the CO_2 bearing zone. The bottom layer of the negative change is thicker than the top layer of that and becomes deeper the depth during the post-injection phase. The thickness of CO_2 bearing zone indicated by the neutron porosity and P-wave velocity is not respond at all. On the other hand, at the OB-4 the thickness of CO_2 bearing zone seems to become thicker with time during the post-injection phase. The difference between the OB-2 and OB-4 will cause by the location of the observation wells.

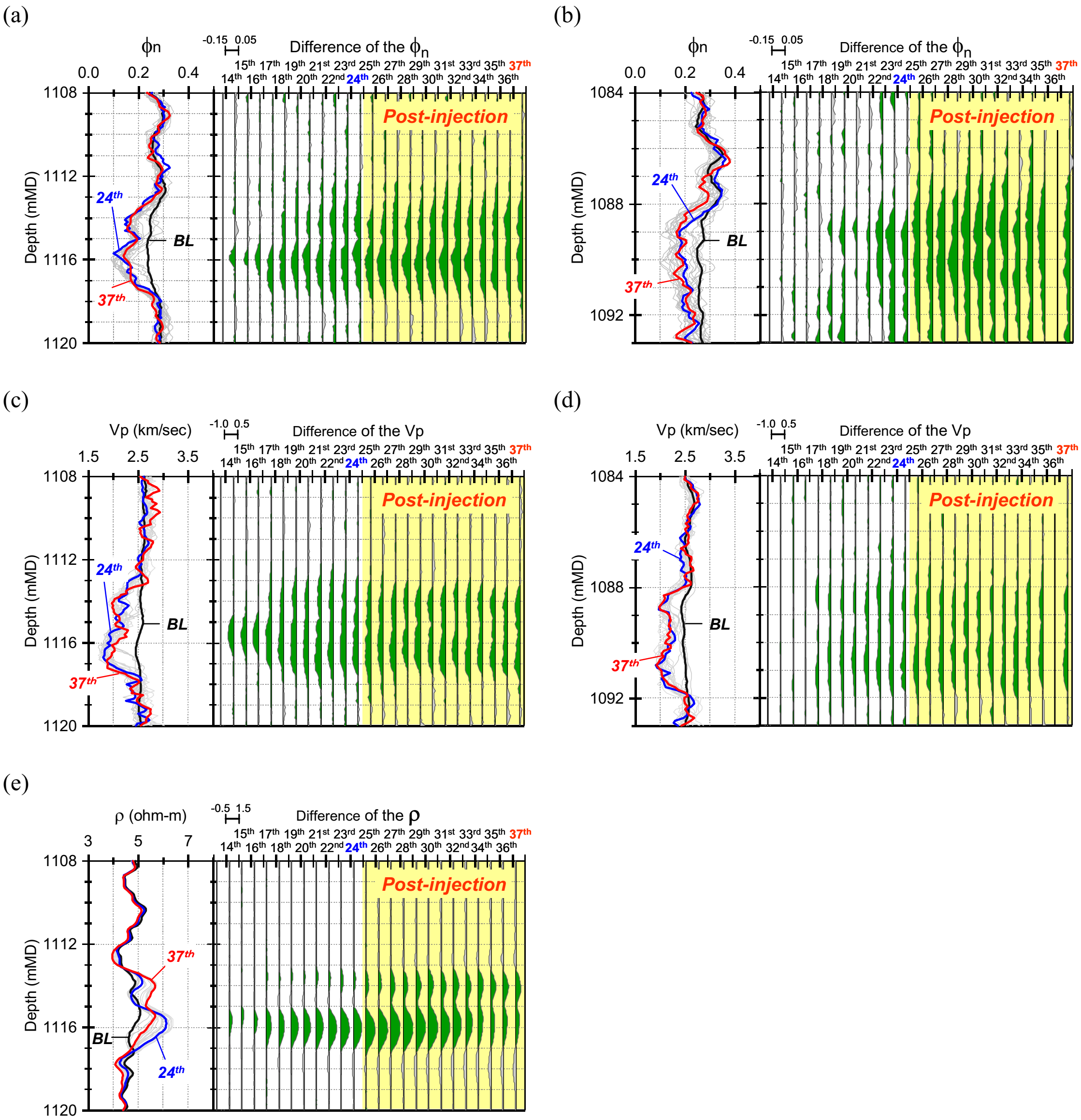

Figure 3 Vertical distribution of neutron porosity (ϕ_n), P-wave velocity (Vp) and resistivity (ρ) in the Zone2 at the OB-2 ((a), (c), (e)) and OB-4 ((b), (d)). The 24^{th} log was obtained just after ceasing of CO_2 injection (13 January 2005). The 37^{th} log is the latest log during the injection and monitoring project (4 December 2007). Baseline (BL) is estimated by averaging logs before arriving CO_2 at the observation wells, 1^{st} (25 June 2003) to 13^{th} (12 February 2004) logs for the OB-2 data while 1^{st} to 16^{th} (12 May 2004) logs for the OB-4 data. Difference is calculated subtraction of the baseline data from the log of each time. Green colour indicates influence of CO_2 replaced with formation water. Yellow coloured area denotes the post-injection phase.

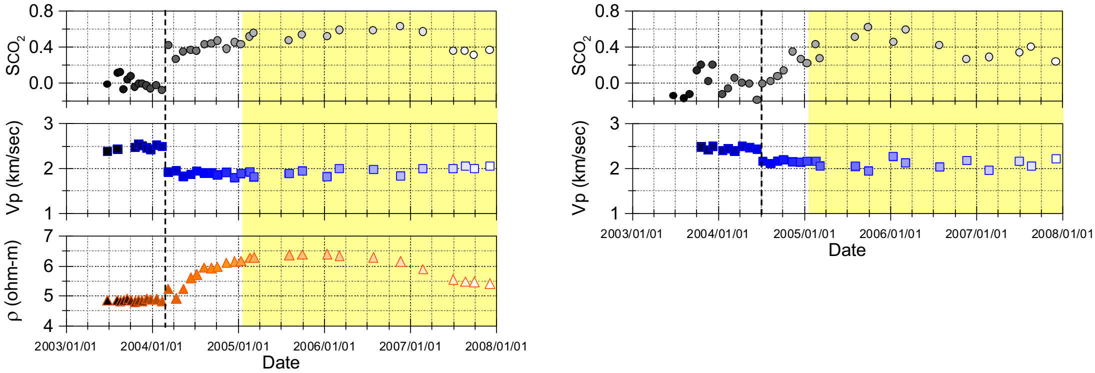

Figure 4 Temporal change of CO_2 saturation, P-wave velocity (Vp) and resistivity (ρ) at the depth of 1116.0 m at the OB-2 (a) and 1090.1 m at the OB-4 (b). Dashed line indicates CO_2 arrival time at the observation wells. Yellow coloured area denotes the post-injection phase.

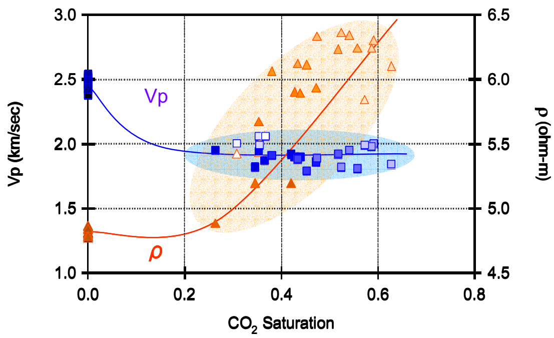

Figure 5 Changes in P-wave velocity (square) and resistivity (triangle) with CO_2 saturation at the depth of 1116.0 m of the OB-2. Coloured lines and areas are the guide to eyes.

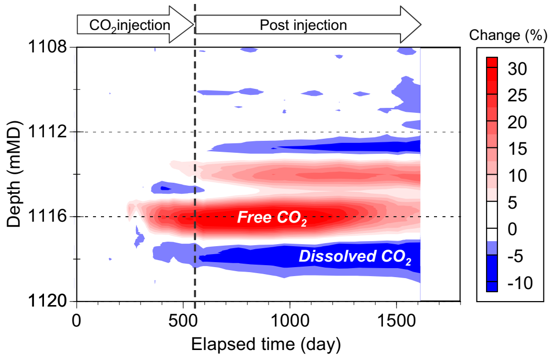

Figure 6 Temporal change of the resistivity in the Zone 2 at the OB-2. Around 1116 m and 1114 m, existence of free CO_2 is explained by increase of resistivity. On the other hand, decrease of resistivity above and below CO_2 bearing layers indicates existence of dissolved CO_2.

5. Discussions

During the injection phase, excess pressure from the injection well forced CO_2 spreading out. The less wetting CO_2 displaces the more wetting formation water in a drainage-like process. It is considered that the buoyant CO_2 migrates up direction and replaces formation water at the trailing edge of the plum after ceasing of injection [7]. This process is so called an imbibition-like process. In an imbibition phase, solubility trapping is expected to accelerate and residual CO_2 trapping starts working.

At Nagaoka, the CO_2 saturation had increased after ceasing of the injection (Figure 4). These result suggested that drainage process had worked at not only injection phase but also the early post-injection phase. Saturation of CO_2 at the OB-4 was maximum 62% at about 1 year after the cessation and had been decreasing in the lower part of the Zone2. Similarly, CO_2 saturation at the OB-2 was maximum 63% at about 2 years after the cessation and had been decreasing in the lower part of the Zone2. There are two reasons to explain reduction of CO_2 saturation. One is dissolution of free CO_2 in the formation water. The other is replacement of CO_2 with formation water. Here, CO_2

saturation is assumed by neutron porosity which obtained from counting an amount of hydrogen in the water. Moreover resistivity change was still positive at the depth of 1116.0m of the OB-2. It means that there are free CO_2 in the reservoir. Thus decrease of CO_2 saturation in the CO_2 bearing layer considered to result in the imbibition process. This imbibition process shows an evidence of residual trap in progress at Nagaoka. Continuous monitoring will provide an existence of immobile CO_2 or an evidence of residual gas trapping.

The resistivity of the lower part of CO_2 bearing zone changed positive value to negative value compared to the baseline data (Figure 6). The thickness of positive resistivity area became thin with time while negative area became thick. The fluid sample from the resistivity area showed increase of dissolved CO_2 within the reservoir (Mito et al. 2008). Dissolution of CO2 results in 7.2% increase of salinity at the depth of 1118.0m of OB-2 in 11 months after ceasing of injection. This change in salinity is roughly consistent with the change in resistivity (6.5%). Relatively large amount of resistivity change was attributed to the low salinity (0.8%) of the initial formation water at Nagaoka. It is confirmed that solubility trapping has been actually working at the Nagaoka.

6. Conclusions

At Nagaoka, the drainage process continued in the early stage of the post-injection phase. After nearly stabilizing pressure, imbibition process started. The results of time-laps well logging provide the evidences of the solubility trap and residual trap in progress at Nagaoka. To study an imbibition process in the post-injection phase, we could learn issues that remain to be solved for long-term safety of CO_2 geological storage.

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